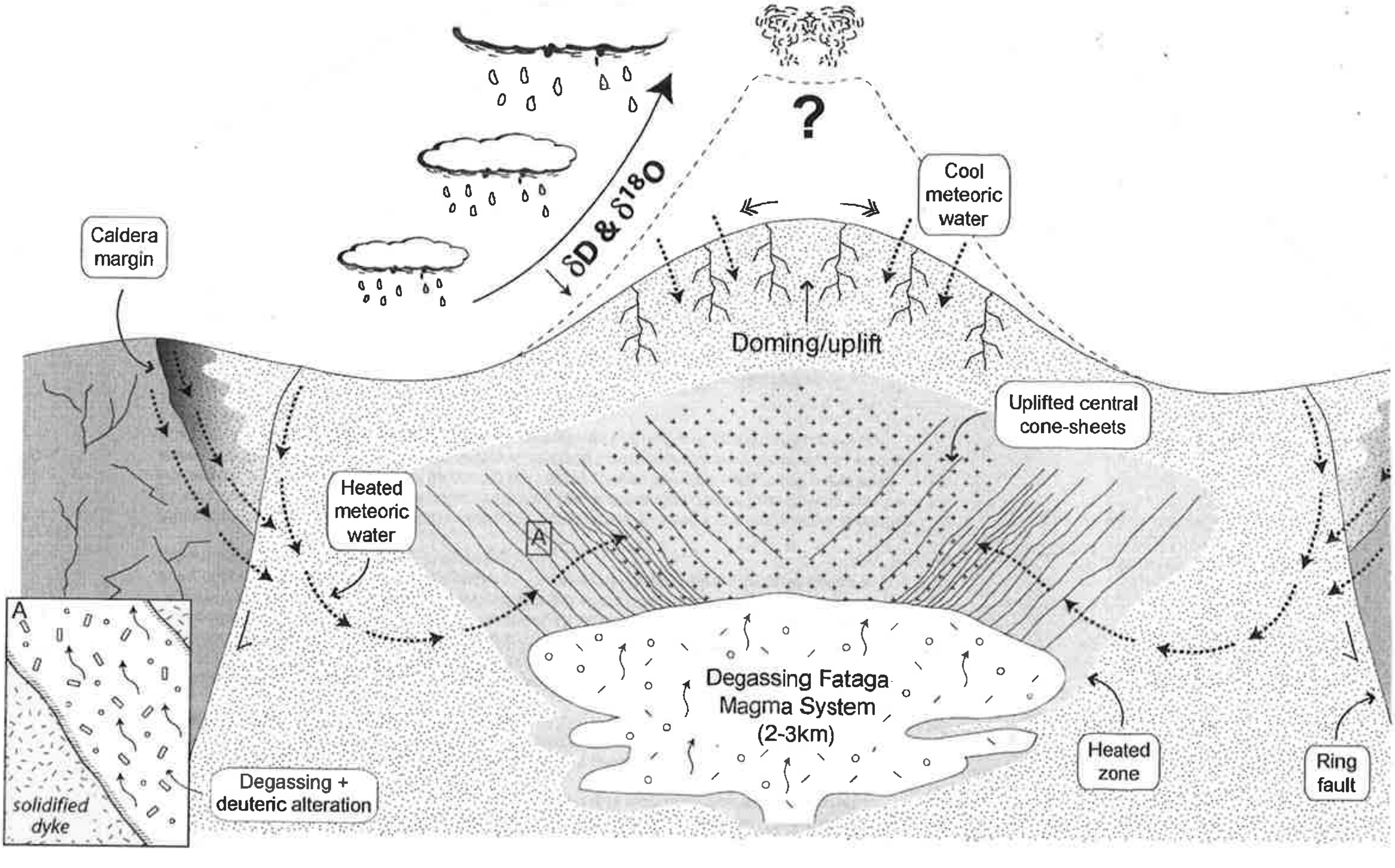
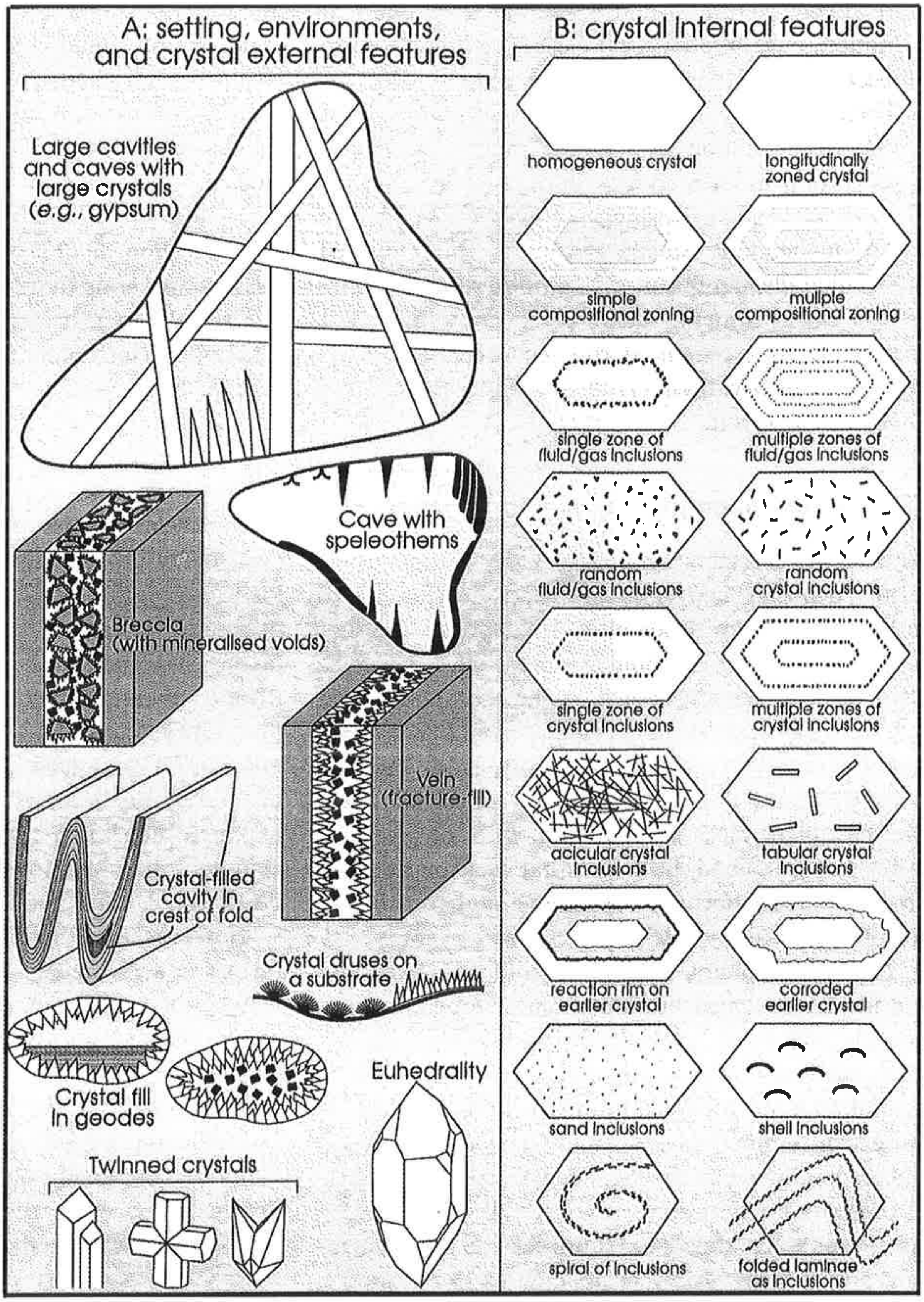
Practical Part

- Rock-forming Minerals
- Glossary of igneous textures
- Thin section petrography
- Homeworks



Key igneous minerals

MINERAL	Hand specimen	Microscope (in PPL)	Microscope (in CPL)	Additional microscope features
[redacted]	**Ferro**	**magnesian**	**(Mafic)**	[redacted]
Olivine **$(Mg, Fe)_2 SiO_4$** **Island silicate**	Green / olive in colour	Light green to transparent	Very high interf. colours (3rd order). Straight extinction.	No cleavage, irregular cracks, often resorbed
Clinopyroxene **Ca, Mg, Si_2O_6** **Chain-silicate**	Black to brown	Brown to black to green	High interf. colours (2nd order). Inclined extinction.	90° cleavage, sometimes zoned (8-sided)
Amphibole **$(Ca,Na,K)_{2\text{-}3}$** **$(Mg,Fe_{2+},Al_{3+})_5[OH$** **$(AlSi_3)O_{11}]_2$** **Double-chain-silicate**	Black to brown	Brown to black with strong pleochroism	High interf. colours (2nd order). Inclined extinction.	120° to 60° cleavage (diamond-shaped) (6-sided)
Biotite **$K(Mg,Fe_{2+})_3[(OH)_2$** **$(Al,Fe_{3+})Si_3O_{10}]$** **Sheet-silicate**	Black, shiny + flaky, very soft	Brown with minor pleochroism	Very high interf. colour (3rd order)	Birds-eye structure (finest lamellae)
	Felsic	**Minerals**		
Plagioclase **$Na[Al,Si_3O_8]$ to** **$Ca[Al_2Si_2O_8]$** **Framework-silicate**	White + stumpy, sometimes grey or when extremely fresh then transparent	No colour, ie. transparent. Sometimes in clusters in volcanic rock (glomerocrysts).	Pyjama stripes white – grey to black (1st order colours)	Cleavage + zoning often present
K-feldspar **(Ka,Na) $[Al2SiO_2O_8]$** **Framework-silicate**	White, pink, often platy, Karlsbad-twins might occur	No colour, transparent	Grey to black often with perthite. If low-T then tartan twinning	Cleavage and broad twinning sometimes present
Quartz **SiO_2** **Framework-silicate**	Transparent grey, often texturally late	No colour, transparent	Grey to black. Interf. Colours of 1st order	Undulous (patchy) extinction
Muscovite **$KAl_2[(OH,F)_2$** **$Al,Si_3O_{10}]$ sheet-silicate**	Silvery shiny + flacky, very soft	Grey to light brown	Intense colour of higher order	Bird-eye structure



A: setting, environments, and crystal external features
Large cavities and caves with large crystals (e.g., gypsum)
Cave with speleothems
Breccia (with mineralised voids)
Vein (fracture-fill)
Crystal-filled cavity in crest of fold
Crystal druses on a substrate
Crystal fill in geodes
Euhedrality
Twinned crystals
B: crystal internal features
homogeneous crystal
longitudinally zoned crystal
simple compositional zoning
muliple compositional zoning
single zone of fluid/gas inclusions
multiple zones of fluid/gas inclusions
random fluid/gas inclusions
random crystal inclusions
single zone of crystal inclusions
multiple zones of crystal inclusions
acicular crystal inclusions
tabular crystal inclusions
reaction rim on earlier crystal
corroded earlier crystal
sand inclusions
shell inclusions
spiral of inclusions
folded laminae as inclusions

— Notes and Comments —

OLIVINE GROUP Orthorhombic

$(Mg,Fe)_2[SiO_4]$

Forsterite (Fo) Mg_2SiO_4

Fayalite (Fa) Fe_2SiO_4

Colour	Usually colourless. May appear pale yellow if high in Fe^{2+}
Pleochroism	Extremely rare Fa - a + ß pale yellow and yellow
Habit	equant, tabular, acicular, dendritic (< Mg more dendritic). anhedral plutonic subhedral/rough 6-sided phenocrysts extrusive
Cleavage	v poor {010} {100} imperfect parting
Relief	variable Fo moderate-high 1.635-1.670 Fa very high 1.824-1.875
Alteration	Very susceptible (hydrothermal/ low grade meta^{m}/ weathering) Serpentine, chlorite, talc, carbonate, Fe oxides, iddingsite, bowlingite.
Birefringence δ	High - =lower 3rd d (max if *Fe rich*)
Interference Figures	2V very large single isogyre from isotropic section Fo_{85}-Fa_{15} - $Fo_{50}Fa_{50}$ = 90°-75°
Extinction	Straight
Twinning	Rare
Other	Zoning occassionally *Mg rich* may have exsolved inclusions of chromite/magnetite * Iddingsite - reddish brown RI 1.76-1.89 (smectite, chlorite. goethite/haematite) * Bowlingite - green allteration (smectite, chlorire, serpentine, talc, mica,qtz) * type depends on oxidation state of Fe higher d on edge of X^{l} = higher Fe content
Distinguishing features	*Mg rich* from Diopside - poorer cleavage and larger optic axial angle and higher d. *Fe rich* from Epidote - yellow/green pleochroism, larger optic axial angle and oblique extinction.

PYROXENE GROUP

Magnesium- Iron Pyroxenes	
Orthopyroxene – Enstatite - ferrosilite	$(Mg,Fe)_2Si_2O_6$
Clinoenstatite-clinferrosilite	$(Mg,Fe)_2Si_2O_6$
Pigeonite	$(Mg,Fe^{2+},Ca)(Mg,Fe_{2+})Si_2O_6$
Calcium Pyroxene	
Diopside-Hedenbergite	$Ca(Mg,Fe)Si_2O_6$
Augite	$(Ca,Mg,Fe^{2+},Al)_2(Si,Al)_2O_6$
Calcium-Sodium Pyroxene	
Omphacite	$(Ca,Na)(Mg,Fe^{2+},Fe^{3+},Al)Si_2O_6$
Aegirine-augite	$(Ca,Na)(Mg,Fe^{2+},Fe^{3+})Si_2O_6$
Sodium Pyroxene	
Jadeite	$NaAlSi_2O_6$
Kosmochlor	$NaCrSi_2O_6$
Aegirine	$NaFe^{3+}Si_2O_6$
Lithium Pyroxene	
Spodumene	$LiAlSi_2O_6$

'Normal' Px - seen in basic, calc-alkaline and in some ultrabasic and intermediate rocks.
Na – Px - alkaline igneous rocks.

Exsolution lamellae: Slowly cooled Px especially Opx and augites, often contain lamellae of definite crystallographic orientation.

E.g. Opx crystallises first at a high temperature with some Ca in the structure. It then cools and some of the Ca in the crystal is exsolved as CPx parallel to {100} planes.

- Opx - CPx lamellae is parallel to {100} planes
- Ca rich CPx - exsolved Opx parallel to {100}
  pigeonite parallel to {001}

Crystallisation trends

Start				Finish
A Mg rich Opx		pigeonite		
B Mg rich augite	———	———	ferro-augite ———	ferro-hedenbergite
C Mg rich Ol	———	hiatus ———	fayaltic(Fe rich Ol)	
Mg:Fe	70:30	35:65		

——— decreasing Mg:Fe ratio ———

ORTHOPYROXENE Enstatite (En) – Orthoferrosilite (Fs)

Colour	Mg rich colourless Fe rich pale green – pale brown
Pleochroism	Some coloured Opx faintly pleochroic brown-yellow-green
Habit	Early formed crystals short prismatic
Cleavage	2 good {110} ⊥ on basal section
Relief	Moderate- high
Alteration	Opx → serpentine also amphibole (during which sometimes Fe oxides are released)
Birefringence δ	Low first order greys (En) – yellow/reds (Fe rich)
Interference Figures	Large biaxial
Extinction	Straight to edge/cleavage
Twinning	Absent
Others	Exsolution lamallae
Distinguishing features	OPx distinguished from CPx by parallel extinction

CLINOPYROXENE Diopside (Di) – Hedenbergite (Hed)

Colour	Di – colourless Hed – brownish green
Pleochroism	Hed – weakly pleochroic from pale green/brown (**NOT** diagnostic feaure)
Habit	Short subhedral crystals
Cleavage	{110} good. Basal intersection 87°. Partings present
Relief	Moderate- high
Alteration	Similar to Opx Di rarely to chlorite
Birefringence δ	Moderate – mid 2nd order greens and yellows
Interference Figures	Moderate 2V
Extinction	Large angle - various
Twinning	Single and multiple common
Others	Exsolution lamallae
Distinguishing features	Di - basic extrusives Hed - acid

Pigeonite

Similar to Di and augite (2V small <30°)

δ very low 1st order greys

2 cleavages meeting at <90°

Occurring in rapidly chilled rocks. Undergoes transformation into Opx if slowly cooled.

AUGITE

Colour	Colourless to pale brown Titanaugite pale purple
Pleochroism	Very weak. Titanaugite weakly pleochroic pale green-pale brown.
Habit	Variable subhedral prismatic crystals (plutonic) → euhedral (basic extrusive)
Cleavage	Similar to diopside {110} good, partings visible
Relief	Moderate- high
Alteration	Similar to Diopside
Birefringence δ	Moderate – low 2nd order blues and greens
Extinction	Similar to diopside
Twinning	Similar to Diopside
Others	Hourglass zoning especially titanaugite
Distinguishing features	Virtually indistinguishable from Di except may have smaller 2V
Occurrence	Augite mafic and ultramafic plutonic rocks Diopside – metamorphic and basic volcanics

AMPHIBOLE GROUP

Inosilicates
Orthorhombic/monoclinic

Anthophyllite – gedrite group

Ca poor (Ca & Na nearly zero)
Orthorhombic and monoclinic

$\mathbf{X_2Y_5Z_8O_{22}(OH,F)_2}$

X= Mg,Fe,
Y= Mg,Fe,Al
Z= Si,Al

Hornblendes and tremolite-ferroactinolite group

Ca rich (Ca>Na)
Monoclinic

$\mathbf{AX_2Y_5Z_8O_{22}(OH,F)_2}$

A= Na
X= Ca
Y= Mg, Fe, Al
Z= Si,Al

Glaucophane-riebeckite, richterite and ockermannite- arfvedsonite group

Alkali (Na>Ca); Monoclinic

$AX_2Y_5Z_8O_{22}(OH,F)_2$

A=Na
X= Na or (Na,Ca)
Y= Mg, Fe, H
Z= Si, Al

General

Colour	Green, yellow, brown (pale/strong) Mg rich - colourless or pale coloured with slight pleochroism Fe rich and alkali – strongly coloured and pleochroic
Habit	Elongated prismatic – diamond shaped cross sections
Cleavage	2 prismatic cleavages - intersection angles at 56° (acute angle)
Relief	Moderate - high
Alteration	Usually to chlorite or talc (with water)
Birefringence δ	Low to moderate – upper 1^{st} or low 2^{nd} order Fe rich high interference colours but strong body colours of alkali mask δ.
Interference figure	Large 2V except glaucophane/katophorite. Alkali not seen
Extinction	Orthorhombic – straight extinction Monoclinic - variable
Twinning	Common on {100} single or multiple
Zoning	Fairly common
Occurrence	Ca poor and Ca rich rarely seen in rocks unless metamorphosed.

HORNBLENDE $Na_{0-1}Ca_2(Mg_{3-5}Al_{2-0})(Si_{6-7}Al_{2-1})O_{22}(OH,F)_2$

Colour	Variable light brown, green, darker colours if Fe rich
Habit	Prismatic crystals usually elongated
Pleochroism	Variable with pale green/brown/dark green Fe rich – yellow/brown/green
Cleavage	2 prismatic cleavages - intersection angles at 56° (acute angle)
Relief	Moderate - high
Alteration	See general note
Birefringence δ	Moderate –low 2^{nd} order blues but strong body colours of Fe rich mask δ.
Interference figure	See general
Extinction	See general
Twinning	See general
Occurrence	Can appear as corona to Ol crystals in some basic rock 1^{st} minerals in intermediate plutonic igneous rocks Mg rich in basic, Fe rich in acidic

RIEBECKITE Monoclinic

$Na_2(Fe^{2+}Fe^{3+})Si_8O_{22}(OH)_2$

Colour	Dark blue - greenish
Habit	Large subhedral prismatic crystals or tiny crystals in groundmass of alkali microgranites
Pleochroism	Common blue/deep blue/yellow green
Cleavage	See general
Relief	Moderate - high
Alteration	Common – asbestos. Found in intimate association with Na-Px (aegirine) alkali granites and syenites
Birefringence δ	Low - moderate –masked by strong body colours
Interference figure	Occassinoally strong body colours mnake it hard to obtain
Extinction	Length fast 6-8° {010} will give maximum angle
Twinning	Simple or multiple on {100}
Distinguishing feature	Dark blue and length fast
Occurrence	Alkali igneous rocks – alkali granites associated with aegerine

Katophorite

$Na_2Ca(Mg,Fe)_4Fe^{3+}(Si_7Al)_{22}(OH)_2$

Dark coloured alkali intrusives associated with nepheline, aegirine and arfvedsonite

Oxyhornblende

$NaCa_2(Mg,Fe,Fe^{3+},Ti,Al)_5(Si_6Al_2)O_{22}(O,OH)_2$

(basaltic honblende)

Phenocrysts in intermediate volcanic or hyperbyssal

Andesites, trachytes etc

Kaersutite

$(Na,K)Ca_2(Mg,Fe)_4Ti(Si_6Al_2)O_{22}(OH)_2$

Alkaline volcanic rock,

Phenocrysts in tracyte and other K rich extrusives, occasionally monzonites.

Eckermannite-arfvedsonite monoclinic

$Na_2Na(Mg,Fe^{2+})_4AlSi_8O_{22}(OH,F)_2$

Pleochroic - green/ blue green/ yellow

Moderate to high relief

Alkali plutonic rocks (Na rich) – nepheline syenites and qtz syenites association with aegirine-augite and apatite

Late stage crystalisation products`

FELDSPAR GROUP

Tektosilicates

Alkali	Orthoclase → Albite	$(K,Na)[AlSi_3O_8]$
Plagioclase	Albite → anorthite	$Na[AlSi_3O_8] - Ca[Al_2Si_2O_8]$

GENERAL

Colour	Colourless with white or brown patches depending on whether alteration (clay minerals) has taken place
Habit	Phenocrysts - euhedral → tabular/prismatic Prismatic subhedral or anhedral
Cleavage	2 {001} {010}, intersecting at nearly right angles on {100} section. Partings occur
Relief	Low K feld <1.54 Plag >1.54
Alteration	Clay minerals
Birefringence δ	Max 1st order whites in Ca poor plag, yellows in Ca rich plag.
Extinction	Repeated twinning – symmetrical extinction angle used to measure plag composition
Twinning	K rich alk feld – simple Plag feld polysynthetic twinning/ repeated/ multiple twins.
Zoning	Common in plag particularly extrusive phenocryts
Distinguishing features	'Newcastle strip' twinning Perthites – unmixing/exsoplution intergrowths of - K in plag or plag in K.

ALKALI

Sanidine – high Albite	Ab_{0-63}	Sanidine
	Ab_{63-90}	Anorthoclase
	Ab_{90-100}	High Albite
Orthoclase- low Albite	Or_{100-85}	Orthoclase
	Or_{85-20}	Orthoclase cryptoperthites
	Or_{20-0}	Low Albite
Microcline – low Albite	Or_{100-92}	Microcline
	Or_{92-20}	Microcline cryptoperthites
	Or_{20-0}	Low albite

Colour	Colourless – opaque patches of alteration
Habit	High temp porphyrtic - euhedral prismatic Plutonic intrusives - anhedral
Cleavage	2 {001} {010}
Relief	Low <1.54
Alteration	Clay minerals – limited water → illite, excess water → kaolin
Birefringence δ	Max 1st order whites greys.
Interference figure	2V 40-65°
Extinction	Varies depending on composition
Twinning	Simple or microcline cross hatched
Perthites	Na feld in K feld
Distinguishing features	Anorthoclase – 2 sets of twins – grid/hatch Extrusive only Microcline - plutonic – large 2V (67°) impossible to obtain Orthoclase – like qtz but IR <1.54 Alters easily Biaxial –ve, slightly larger 2V than sanidine
Occurrence	Alkali – acid – syenites,granites and granodiorites, felsites. Orthoclase porphyries, tracytes, rhyolitres and dacites Common in pegmatites and hydrothermal veins Plutonic – orthoclase, microclinme and perthites Extrusive - sanidines

PLAGIOCLASE

Albite	0-10 %An	$NaAlSi_3O_8$
Oligoclase	10-30 %An	
Andesine	30-50 %An	
Labradorite	50-70 %An	
Bytownite	70-90 %An	
Anorthite	90-100 %An	$CaAl_2Si_2O_8$

Colour	Colourless – opaque patches of alteration
Habit	Plutonic/hypabyssal -Subhedral prismatic Extrusive – euhedral prismatic
Cleavage	2 {001} {010}
Relief	Low >1.54
Alteration	Clay minerals – limited water → montmorillonite, excess water → kaolin
Birefringence δ	Max 1st order greys (Ab)/ yellows (An).
Interference figure	2V large and variable in sign
Extinction	Measure composition using symmetrical extinction angle of albite twins
Twinning	Multiple twinning (Newcastle strip) Na plag – narrow Ca plag – narrow and broad alternation Carlsbad - simple Pericline - repeated
Zoning	Common in extrusives – from Ca rich core → Na rich margin
Occurrence	Bytownite – ultrabasic Labradorite – basic Andesine – intermediate Oligoclase – acid

NEPHELINE

Feldspathoid

$NaAlSiO_4$

Colour	Colourless
Habit	Anhedral occurring in interstices between minerals. Found as exsolved blebs with feldspar (particularly K feld). Euhedral crystals are hexagonal
Cleavage	{1010} imperfect
Relief	Low
Alteration	May alter to zeolites → natrolite/ analcime or sodalite
Birefringence δ	Low - 1st order greys, small inclusions give a night sky effect
Twinning	rare
Occurrence	Characteristic primary crystallising mineral of alkali igneous rocks. Essential in silica deficient nepheline syenites. May be metasommatic in origin

SERPENTINE
$Mg_3Si_2O_5(OH)_4$

Monoclinic
Phyllosilicate

Chrysotile fibrous
Lizardite and **Antigorite** tabular

Colour	Colourless to pale green
Habit	Chrysotile fibrous parallel to x-axis Lizardite and antigorite flat tabular
Cleavage	Chrysotile - fibrous Lizardite - basal
Relief	Low
Birefringence δ	Low to very low 1st order greys, often anomalous pale yellow
Interference Figures	Chrysotile length slow
Extinction	Straight on fibres, cleavage or edge
Other	Textures can be pseudomorphous after i.e olivine – mesh/ hourglass pyroxene - bastite
Distinguishing features	Serpentine minerals have a lower relief and d than chlorite and fibrous amphibole Chlorite often exhibits stronger d or anomalous colours
Occurrence	Formation after alteration of ultrabasic (dunites/ pyroxenites/ peridotites.

CHLORITE
$(Mg,Fe^{2+}, Fe^{3+}, Mn, Al)_{12}[(Si, Al)_8O_{20}](OH)_{16}$

Monoclinic
Phyllosilicate

Colour	Colourless to green
Pleochroism	Green varieties – pale green to colourless or darker green If Fe rich pale yellow to green
Habit	Tabular with pseudo-hexagonal shape
Cleavage	Perfect {001} basal cleavage
Relief	Low to moderate
Birefringence δ	Very low some anomalous colours – deep Berlin blue Mg rich – browns Fe rich - violet/ blue
Interference Figures	Rarely obtained
Extinction	Straight to cleavage
Distinguishing features	Pleochroism
Occurrence	Formation from hydrothermal alteration of pyroxene, amphibole and biotite

ZIRCON Tetragonal

$Zr(SiO_4)$

Colour	Colourless to pale brown
Habit	Very squat, small square prism with terminal faces, euhedral crystals
Cleavage	Imperfect and poor
Relief	Extremely high
Alteration	none
Birefringence δ	Very high 3rd or 4th order
Extinction	straight
Twinning	rare
Distinguishing features	Tiny euhedral crystals in alk or acid plutonic rocks. Cassiterite and rutile have higher RI and δ and are more reddish in thin section.
Occurrence	Accessory mineral in all igneous rocks but essentially intermediate → acid associated with biotite

MICA GROUP Phyllosilicates

$X_2Y_{4-6}Z_8O_{20}(OH,F)_4$

X= K, Na (Ba, Rb, Cs, Ca)
Y= Mg Fe Al (Mn, Li, Ce, Ti, V, Zn, Co, Cu, V)
Z= Si, Al (Ti, Ge)

PHLOGOPITE Monoclinic

$K_2(Mg,Fe)_6Si_6O_{20}(OH,F)_4$

Colour	Pale brown - colourless
Habit	Small tabular crystals
Pleochroism	Weak – yellow/brownish red/ green/ deeper yellow
Cleavage	Perfect {001}
Relief	Low - moderate
Birefringence δ	High 3rd order – body colours can mask
Extinction	Usually straight
Twinning	Rare
Other	Reaction rims found in kimberlite intrusions
Occurrence	Common constituent of kimberlite Minor constituent of ultramafic rocks

BIOTITE Monoclinic

$K_2(Mg,Fe)_{6-4}(Fe^{3+},Al,Ti)_{0-2}Si_{6-5}Al_{2-3}O_{20}(OH,F)_4$

Colour	Brown or yellowish occasionally green
Habit	Tabular and subhedral hexagonal plates
Pleochroism	Common and strong – yellow/brown
Cleavage	Perfect {001}
Relief	Moderate
Alteration	Common in hydrothermally altered rocks → chlorite
Birefringence δ	High – very high– body colours can mask
Extinction	Nearly straight on cleavage – speckled appearance near extinction
Twinning	Rare
Occurrence	Primary crystallising in acid-intermediate plutonic rocks Not common in acid and intermed. hypabyssal nad extrusives

MUSCOVITE

$K_2Al_4Si_6Al_2O_{20}(OH,F)_4$

Colour	Colourless
Habit	Thin platy crystals
Cleavage	Perfect {001}
Relief	Low to moderate (particularly in Fe is present)
Alteration	Absent
Birefringence δ	High – upper 2nd- 3rd order
Extinction	Straight on cleavage
Twinning	Not observable
Occurrence	Late stage component of acid igneous plutonic rocks

QUARTZ ; SiO_2 Triagonal

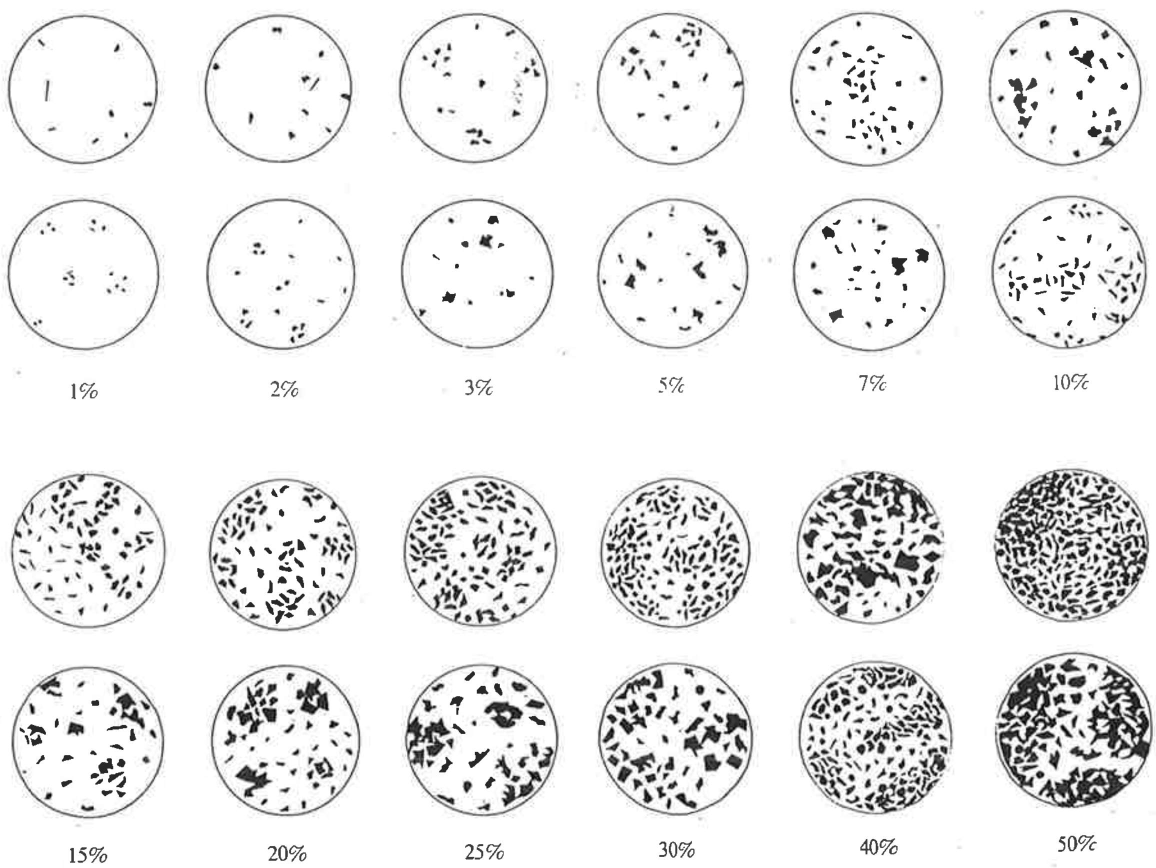
Colour	Colourless
Habit	Euhedral crystal may appear as phenocrysts in acid extrsives but usually shapeless, interstital grains
Cleavage	None
Relief	Low just greater than 1.54
Alteration	None
Birefringence δ	Low – max 1st order yellow
Extinction	Straight on prism edge
Others	May show corroded margin- reaction between quartz and liquid

Tridymite
Rare but may be found in quickly cooled igneous rocks – association with sanidine, augite, fayalitic olivine
Rhyolite, pitchstones, dacites etc
Lower RI <1.54

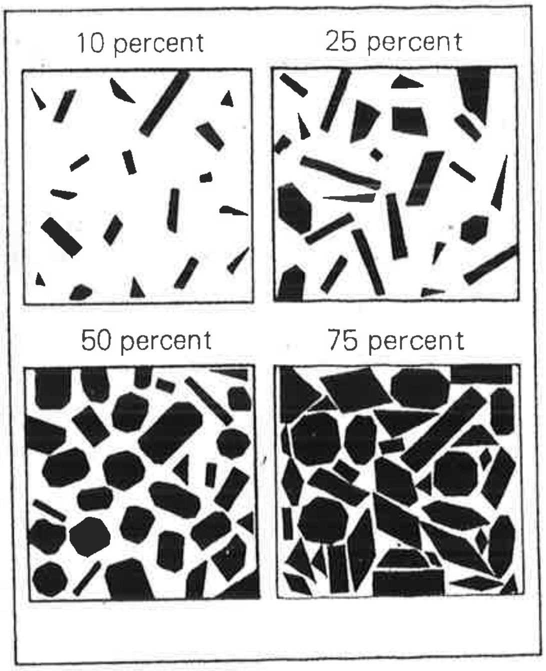
Cristobalite
Found in cavities in volcanic rocks

OXIDES

Spinel	Composition	Colour/ opacity
Spinel	$MgAl_2O_4$	RI=1.719. Colourless or red / brown/ blue
Magnetite	Fe_3O_4	Opaque
Chromite	$FeCr_2O_4$	Opaque – brown on edges
Rutile	TiO_2	Reddish brown/ yellowish. Sometimes opaque – high body colour



Charts to aid the visual estimation of modal proportions of minerals in rocks [After R. D. Terry and G. V. Chilingar, American Geological Institute Data Sheet 6.]


10 percent
25 percent
50 percent
75 percent

HAND-SPECIMEN PRACTICAL

A) GRAIN SIZE:

(coarse: average > 5mm; medium: average 5mm-1 mm; fine: average <1mm)

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These are averages; in general the rock is coarse if all the crystals can be seen with the naked eye, medium if a lens is needed to see the crystals, and fine if even with a lens the crystals are hard to see. Fine rocks are often partly or wholly glassy. Coarse are usually plutonic, medium are hypabyssal, fine are volcanic.

B) ROCK COLOUR (M-Index)

("M" from Greek "melanos" = black. Black is M = 100; white is M = 0).

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Colour Index is the proportion of dark-coloured to light-coloured minerals. The more dark minerals are present the more mafic (=basic) is the rock chemistry. Exception: very fine grained or glassy rocks often appear dark independently of their mineral assemblage.

C) TEXTURE:

(holocrystalline/ partly crystalline/ glassy/ porphyritic/ non-porphyritic)

____

D) MINERAL CONTENT:

What minerals are present ? Estimate vol%.

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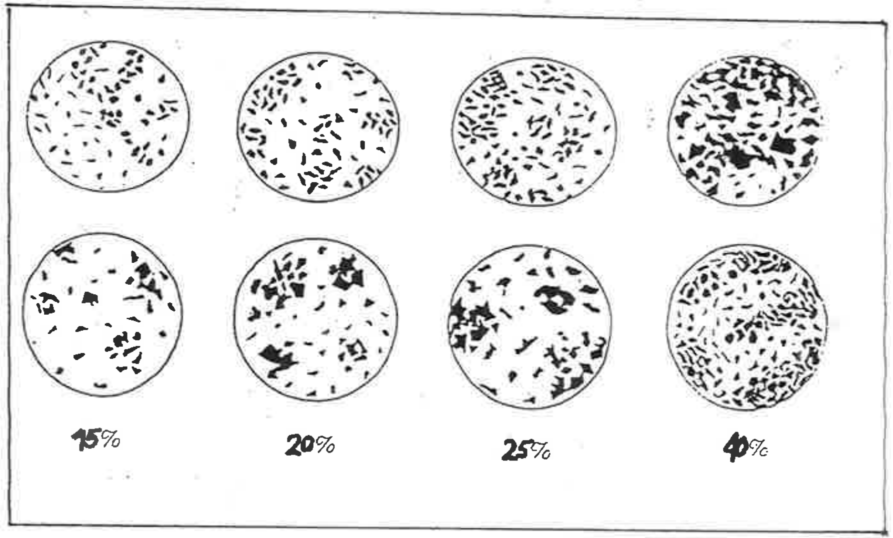
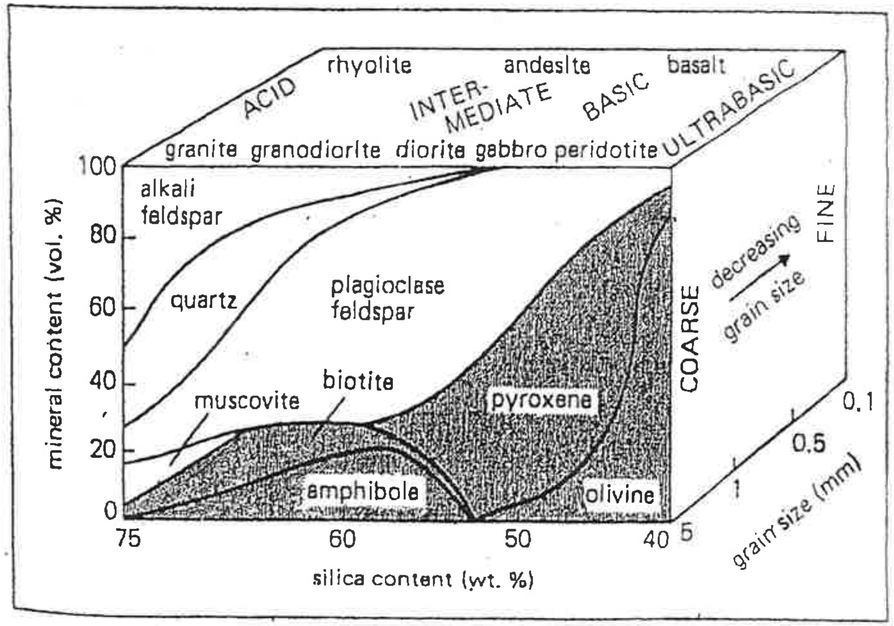
E) CONTENT OF LIGHT MINERALS:______________

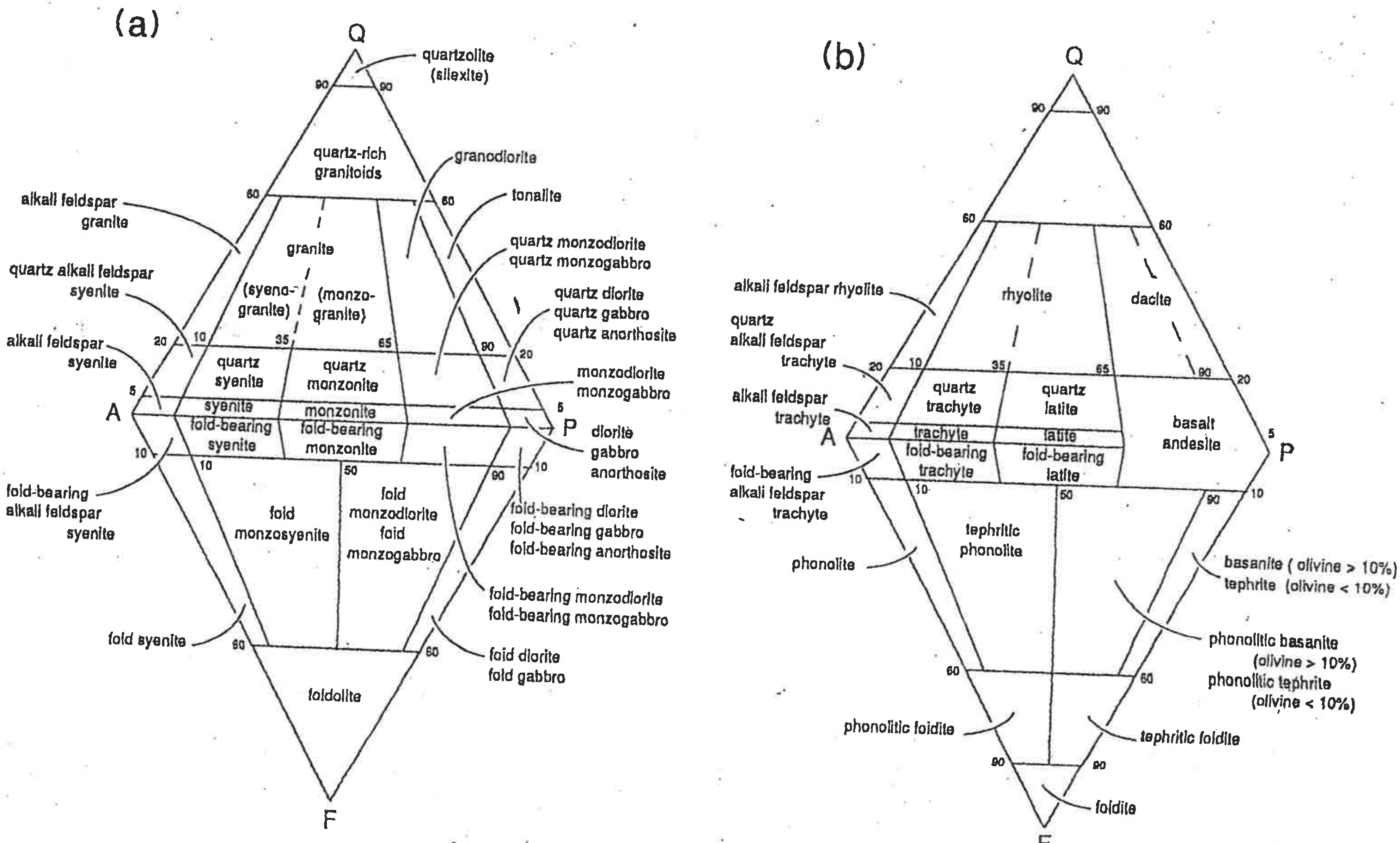
CONTENT OF DARK (FERROMAGNESIAN) MINERALS:______________

ROCK NAME:______________________

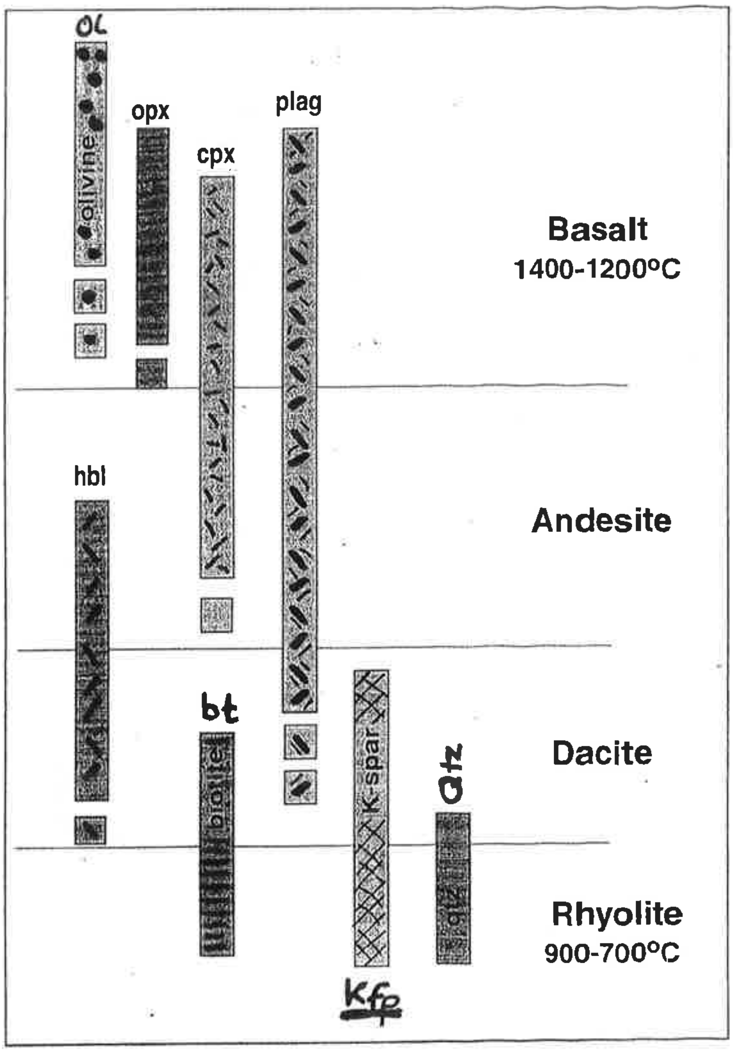




Preliminary classification scheme for igneous rocks using colour index (front face shows approximate proportions of light and dark minerals that occur at different silica contents), common silicate minerals (where recognized in the field) and grain size (decreasing with depth into the diagram).



Classification of (a) plutonic igneous rocks and (b) volcanic rocks according to the relative abundance of Q = quartz, A = alkali feldspar, P = plagioclase, and F = feldspathoid, when the mafic minerals (M) are less than 90% (Le Maitre, 1989).

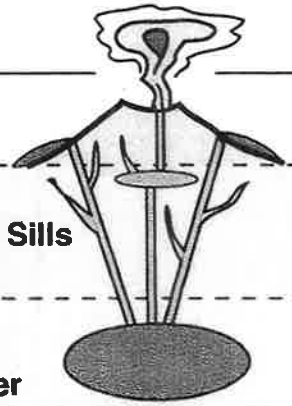


Typical chemical compositions[1] for some major silicate minerals in igneous rocks (weight per cent). See Table 4.6 for distinguishing features in hand specimens of these and other minerals.

	SiO_2	Al_2O_3	FeO + Fe_2O_3	MgO	CaO	Na_2O	K_2O	H_2O
Felsic minerals								
Quartz	100	—	—	—	—	—	—	—
Orthoclase	65	18	—	—	—	—	17	—
Albite	69	19	—	—	—	12	—	—
Anorthite	43	37	—	—	20	—	—	—
Muscovite	45	38	—	—	—	—	12	5
Nepheline	42	36	—	—	—	22	—	—
Mafic minerals								
Olivine	40	—	15	45	—	—	—	—
Pyroxene (augite)	52	3	10	16	19	—	—	—
Amphibole (hornblende)	42	10	21	12	11	1	1	2
Biotite	40	11	16	18	—	—	11	4

[1]Silicate minerals are made up of atomic frameworks in which different combinations of cation-forming elements are always bonded to oxygen and so it is customary to quote analyses in terms of simple oxides rather than elements.

Note also that in most mineral groups there is compositional diversity caused by the ability of atomic frameworks to hold different cations in the same site (e.g. substitution between Fe and Mg, or between Na and Ca occurs in many mineral groups).



	ENVIRONMENT	ROCK TYPE				TEXTURE
Flows	Volcanic	Basalt / Basanite	Andesite / Hawaiite	Dacite / Trachyte	Rhyolite / Phonolite	**Porphyritic**
Dykes / Sills	Hybabyssal	Dolerite	Microdiorite	Micro-granodiorite syenite	Microgranite	**Interstitial/ intersertal +/- glass**
Magma Chamber	Plutonic	Gabbro	Diorite	Granodiorite / Syenite	Granite / Alk. Granite	**Granular**

45%   **55%**   **65%**   **70%**

INCREASING SiO_2 (wt.%)

Glossary of Igneous Rock Textures

This guide is thought to help with the description of igneous rocks textures and is largely based on MacKenzie, Donaldson and Guilford *"Atlas of Igneous rocks and their textures"* Longman Scientific & Technical Publishers. Please bring to all practicals.

Textures may be considered to comprise four properties:
A. Degree of crystallisation ('crystallinity'), that is the relative amounts of crystals and glass in a rock.
B. Sizes of individual crystals ('grain size' or 'granularity')
C. Shapes of individual crystals, and
D. Mutual relations (ie arrangements or patterns) of crystals.
Names associated with each of these properties are listed below.

A. CRYSTALLINITY

- **holocrystalline** - entirely crystalline.
- **holohyaline** - either entirely glass, or mostly glass with scarce crystals (syn. **'glassy'**).
- **hypocrystalline** - partly glass and partly crystals (syn. **'hemicrystalline'**) Notes:

1. Glassy can include very finely crystallised glass (ie **cryptocrystalline texture**, see next section).
2. Tiny crystals in glass are of two types: (a) those too small to have a reaction with crosspolarised light and cannot therefore be identified as a particular mineral; these form globules, rods and hair-like bodies and have the general name **'crystallites'**. (b) Those which are large enough to show polarisation colours and can be identified, these have prismatic, acicular and dendritic (ie branching) shapes and are called **'microlites'**.

B. GRANULARITY

General- terms:
- **phanerocrystalline** - all crystals of the abundant minerals (>5%) can be distinguished without the microscope (ie by naked eye or with a hand lens). Phanerocrystalline includes coarsegrained and medium-grained rocks, defined as having grains >5 mm and between 1-5 mm, respectively. Pegmatitic texture applies to rocks whose grain size exceeds ca. 5 cm.
- **aphanitic** [1, 2] - describes a rock or the groundmass of a porphyritic rock in which no individual crystals can be distinguished by naked eye. It is effectively the same as fine-grained, defined as having grains <1 mm. Two sub-sets of aphanitic texture are: **i. microcrystalline** - a rock or the groundmass of a porphyritic rock in which individual crystals can be identified in thin section using a microscope, and **ii. cryptocrystalline** - a rock or the groundmass of a porphyritic rock that is crystalline but the crystals can only be seen by their action on cross-polarised light and are too small to be identified as specific minerals.

A further breakdown relates to the relative grain size in a rock (see also section D):

- **equigranular texture** - all crystals in the rock are of approximately the same size (note the, word 'approximately', ie they do not have to be exactly the same size).
- **inequigranular texture** - there are crystals of clearly more than one size. A common example is the porphyritic texture (section D).

[1] An aphanitic rock with no phenocrysts is called **aphyric.**
[2] For aphanitic rocks which are known from field evidence to be plutonic or hypabyssal some petrologists may inser the prefix 'micro'.

C. SHAPES OF CRYSTALS

Three sets of terms exist: use set I but be aware of the existence of II and III.

EXTENT OF FACE DEVELOPMENT	I	II	II
Crystal is entirely bounded by its own faces	***euhedral***	idiomorphic	automorphic
Crystal is partly bounded by its own faces	***subhedral***	hypidiomorphic	hypautomorphic
Crystal lacks any faces of its own	***anhedral***	allotriomorphic	xenomorphic

There also exist various terms to specify the habits or 'shapes' of crystals:

• **equidimensional** (syn. equant) - crystal has approximately the same size measured in all directions (such as with a cube or a sphere).
• **inequidimensional** - includes tabular, prismatic and bladed (lath) shapes.
• **embayed crystal** - angular or round cavity or cavities penetrate the margin of the crystal; these contain glass, or devitrified glass, or secondary minerals. The term is not normally used for the junction between two primary minerals where one penetrates the other. (NB many people suppose the term to mean corroded; while embayments may form by corrosion they could also be the result of incomplete growth, ie the term has no genetic connotation)
• **skeletal crystal** - an incomplete crystal which may lack a centre or have an intricate embayed exterior.
• **dendritic crystal** - crystal with a more or less regular branching shape.
• **pseudomorphic crystals** - one mineral has more or less completely replaced another but the distinctive shape of the original crystal is retained (eg serpentine occupying the prismatic shape of a now-replaced olivine).

D. MUTUAL RELATIONS OF CRYSTALS + GLASS+ ROCK FRAGMENTS

Several categories of these can be distinguished for convenience of presentation:

1. EQUIGRANULAR TEXTURES - CRYSTALLS OF ROUGELY UNIFORM SIZE
• **granular** :- bulk of the crystals are anhedral-subhedral (syn. allotriomorphic granular)
• **subhedral granular** - most crystals are subhedral (syn. hypidiomorphic granular)
• **euhedral granular** - most crystals are euhedral (syn. panidiomorphic granular)

2. INEQUIGRANULAR TEXTURES - UNEVEN GRAIN SIZE
• **seriate texture** - crystals show a continuous range of sizes (difficult to prove without a large number of accurate measurements).
• **porphyritic texture** - relatively large crystals (phenocrysts syn. insets) are embedded in a finer-grained groundmass or matrix[3] (This is a very common igneous texture).
• **glomeroporphyritic texture** - phenocrysts are bunched together in clots/aggregates called glomerocrysts
• **polkilitic texture** - relatively small, roughly equant crystals of one or more minerals are scattered without common orientation in larger crystals of another mineral[4].
• **ophitic texture** - this is a variety of poikilitic texture in which inequidimensional crystals rather than equant ones are enclosed (eg bladed plagioclases). If both equant and elongated crystals are enclosed in the larger crystals the term polkilophitic may be used.

[3] The mineral(s) present as phenocryts may or may not be present in the matrix. A porphyritic rock can have a fine-, medium- or a coarse-grained matrix. It is named on the basis of the average grain size of the groundmass only rather than the combination of phenocrysts and groundmass; thus a rock of equal amounts of plagioclase and augite whose groundmass has an average grainsize of 0.5 mm but which contains abundant augite phenocrysts of 5-10 mm is nonetheless called a basalt. If phenocrysts have diameters of 0.5 - 0.05 mm they are called microphenocrysts and the texture is said to be microporphyritic.
[4] The term is not applied to minerals which are accessories (ie <5%) in the rock such as apatite or zircon. Neither is the term ordinarily applied to a porphyritic rock in which the phenocrysts contain inclusions of other minerals.

• **sub-ophitic texture** - applies when the inequidimensional crystals are only partially enclosed in the larger crystals[5].

• **interstitial texture** - many rocks contain wedge-shaped spaces (**interstices**) between randomly-arranged touching elongate crystals (eg this is common in rocks with bladed plagioclase crystals). If some of these are wholly or partially occupied by glass, or by secondary minerals that have replaced glass (eg chlorite, analcite, clays or palagonite, ie yellow-orange altered basalt glass), the term **intersertal texture** is used. [If elongated crystals are not touching, then glass/altered glass surrounds each grain and the term **hyalopilitic texture** is used (syn. **vitrophyric texture**). Where some crystals are touching and some are not, so that glass partially or completely encloses crystals the term **hyaloophitic texture** may be used.] If individual interstices are completely filled with one or more or less equant grains of olivine and/or pyroxene and/or opaque the term **intergranular** (syn. **granulitic**) is used. Occasionally the interstices are empty, ie are occupied by gas, for which **diktytaxitic texture** is used.

3. DIRECTIVE TEXTURES

• **trachytic texture** - a sub-parallel arrangement of bladed or tabular crystals in a fine-grained rock.

• **trachytoid texture** - a sub-parallel arrangement of bladed or tabular crystals in a medium- or coarse-grained rock.

• **banded structure** - at one time this term was used for trachytoid texture. If used at all these days it refers to an alternation of rock units (bands) of contrasting texture and/or relative abundance of minerals (modal mineralogy). The term has largely been displaced by 'layering'.

• **eutaxitic texture** - a texture defined by flattened rock fragments (commonly of pumice) or glass shards in pyroclastic rocks. This is sometimes loosely referred to as banding.

4. INTERGROWTH TEXTURES

• **graphic texture**[6] - a regular intergrowth of quartz and alkali feldspar having the appearance of wedge-shaped Arabic writing, due to apparently isolated wedges and rods of one mineral in the other. Each intergrowth consists of one quartz and one alkali feldspar crystal, thus all the wedges and rods in the intergrowth extinguish as a single unit.

• **granophyric texture** - a variety of graphic/micrographic texture in which the rods/wedges have a crudely radiate arrangement in the host crystal. (This texture is common in microgranites; in the UK the Geological Survey traditionally calls such rocks grartophyres.)

• **spherulitic texture** - a radiate arrangement of very fine fibres of minerals, commonly quartz and feldspar.

• **symplectite texture** - microscopic scale intergrowth of two minerals in which one forms sinuous, worm-shaped rods in the other. Usually carries the genetic assumption that has formed by a reaction after the magma has solidified, ie it is a secondary texture formed in the solid state.

• **myermekitic texture** - a specific combination of minerals in a symplectite intergrowth, worm-shaped rods of quartz in a plagioclase grain. Commonly located at the margin of the grain.

• **exsolution** (syn. **unmixing**) **texture** - an intergrowth of two minerals in which one forms parallel lamellae or rods in a grain of the other (eg plagioclase lamellae in an alkali feldspar grain, as in perthite). Forms after magma has solidified, ie in solid state.

5. CAVITY TEXTURES

• **vesicular texture** - spherieal/sub-spherieal eavities (ves~cles) in a rock. [f very abundant such that the rock is frothy in appearance, the terms scoriaceous (for basalt and andesite) and pumiceous (for dacite and rhyolite) apply.

• **amygdaloidal texture** - vesicles completely or partially infilled with secondary minerals[7].

• **miarolitic texture** - miarolitic cavities are irregular-shaped holes in plutonic and hypabyssal rocks lined with euhedral quartz and feldspar.

---

[5] Porphyritic, poikilitic and ophitic textures are sometimes collectively categorised as hiatal textures indicating that there is a non-continuous, ie broken, range of grainsizes in the rock.

[6] If the rock is fine-grained, the term micrographic texture (syn. micropegmatitic texture) is used.

[7] Sometimes the contents of an amygdale are arranged in concentric bands of two or more minerals causing the amygdale to look like a small eye in section. The term ocellus describes this pattern and a rock with many such amygdales (called ocelli) is described as ocellar.

6. OVERGROWTH TEXTURE

• **corona texture** - as seen in individual crystals, this consists of concentric band(s) of one or more mineral(s) more or less surrounding another (eg an olivine core surrounded by pyroxene, possibly in turn surrounded by hornblende). The term does not apply when the surrounding mineral is the same mineral, differing only solid solution composition.

• **crystal zoning** - variety of corona texture in which the successive stages of growth are picked out by gradual or abrupt changes in the solid solution composition of the crystal, eg a plagioclase crystal with a core of Ango surrounded by a rim or mantle of An75. Adjectives are applied to describe the zoning as **continuous** [steady change], or **discontinuous** [abrupt change(s)], **normal** [progressing outwards from high temperature type to low-temperature type], **reverse** [the opposite], and **sector**, or **hour-glass** [a complex style in which different portions of the crystal have different compositions; these portions are arranges in such a manner as to create a pattern resembling that of an hour-glass]. **Zoning** has also been used to describe the situation in which successive stages of growth are picked out by microscopic/sub-microscopic inclusions arranged in bands parallel to the faces of the crystal.

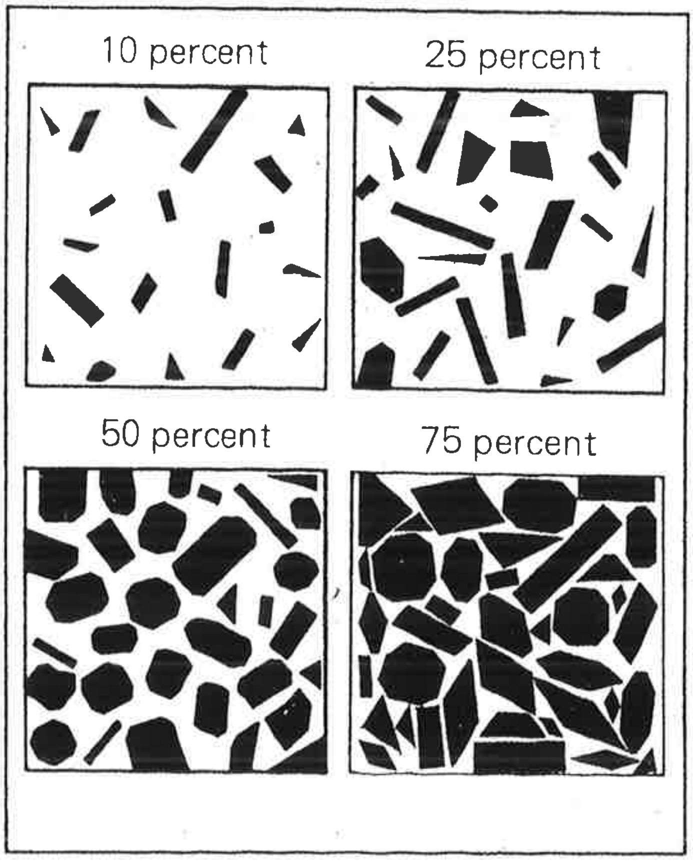
Addenda

• With the exception of eutaxitic texture, the above terms cover non-fragmental igneous rocks. Remember that pyroclastic rocks have a nomenclature based on average fragment size.

• Angular-rounded fragments are sometimes found in crystalline igneous rocks and several words exist for these, including **xenolith** (literally 'foreign rock'), **autolith** (syn. **cognate xenolith**) [fragments of rock genetically related to the host rock, possibly as an early-formed rind on a chamber, the rind subsequently being fragmented when some of the residual magma exited the chamber], **nodule**, and **enclave**. The latter two terms have no genetic connotations. Foreign crystals are called **xenocrysts**.

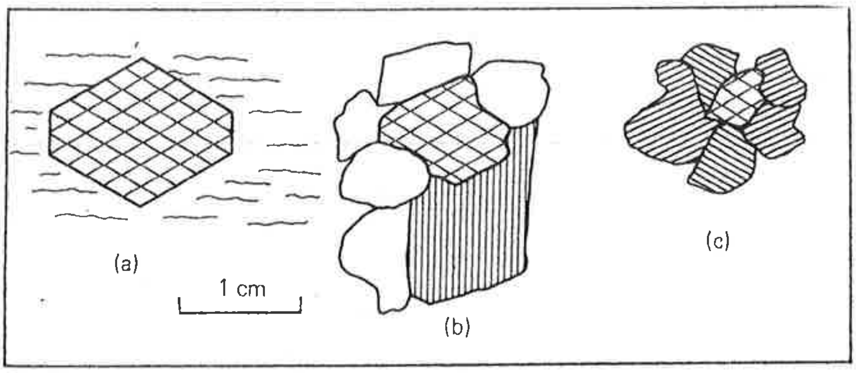
• A special, genetic vocabulary exists for the textures of rocks believed to have formed by the concentration of crystals from magmas, so-called cumulate rocks (see for example Cox et al. Interpretation of Igneous Rocks).

Have fun !



SEOUENTIAL CRYSTALLISATION is the distinguishing feature of igneous rocks and is seen in both Volcanic (porphyritic) and Plutonic (granular) rocks. It leads to a variety of crystal shapes and types of junction between crystals.

- In an igneous rock the crystals grow from a liquid which initially imposes no constraint on their growth, so they develop their own shapes with well developed crystal faces; such crystals are called **euhedral** crystals.
- Eventually, as space becomes used up, the crystals will meet one another and the growth of adjoining faces will be impeded. They will then interlock as growth of free surfaces continues, and will have some original faces and some inter-grown ones. Such crystals are called **subhedral** crystals.
- Later minerals will have to fit into the remaining spaces with whatever shape is available, thus being permitted very few of their own crystal faces. Such crystals are called **anhedral** crystals.



Sketches of (a) euhedral, (b) subhedral and (c) anhedral amphibole crystals

The intergrowth textures are characteristic of igneous rocks. Since liquids don't transmit directional stress, the crystals can grow randomly to produce an isotropic fabric. This is different to the anisotropic, oriented, fabric typical of metamorphic rocks which grow in a solid rock under tectonic stress.

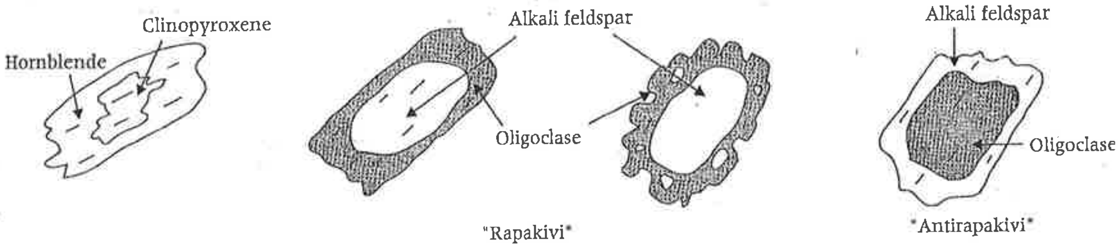
There are three special circumstances in which igneous minerals can orient themselves:

- Flow of liquid during crystallisation - elongated or tabular crystals can align themselves to the flow (like logs in a river). This is most-often seen in dykes and sills in which feldspars align themselves to the magma flow through the narrow fracture.
- . Settling of platy minerals to the bottom of a magma chamber
- Growth of elongate minerals perpendicular to a boundary surface producing a comb-like fabric (like the teeth of a comb). This is seen mainly in hydrothermal veins.
- If an igneous rock displays a directional fabric which is not caused by one of these methods, it has probably been involved in deformational metamorphism during growth - a situation seen most often in granitoid rocks which cool slowly during orogenesis.

Some aspects of texctural development in igneous rocks

Discontinuous Series (ferromagnesian phases)

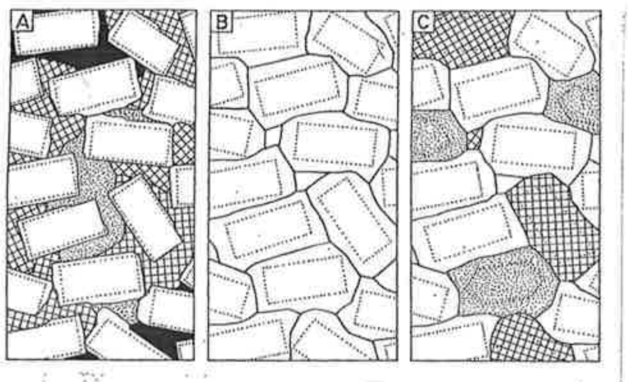
Euhedral minerals continue to grow over the crystallisation temperature range, but may begin to dissolve as temperature falls below this range - this can produce corroded crystals, but since the mineral is attempting to convert to the next in the series, it may develop a mantle of this new mineral (seen as a rim in thin section) which effectively cuts it off from the liquid and stops the conversion.



Crystal settling

In basalt magmas much of the olivine is usually crystallised early and settles to the bottom of the magma chamber, so most gabbros, shallow intrusions and lavas have relatively little olivine and are made up mainly of pyroxene, plagioclase and iron oxide minerals (magnetite, ilmenite). Crystals that have settled from a magma form a cumulate either at the chamber bottom, wall or roof.

Diagrammatic representation of different types of cumulate that might be formed from a gabbroic magma;
A : Plagioclase–orthocumulate,
B : Plagioclase–adcumulate
C : Plagioclase–olivine–pyroxene–adcumulate
Plagioclase – unshaded, olivine – dotted, pyroxene – square grid, iron oxide – black, interstitial quartz and feldspar – dashes. The cumulus crystals are outlined by dotted lines (after Wager 1963).



Crystal morphology

In rocks crystallised from e.g. a granitic magma, the main minerals are Na-plagioclase, K-feldspar and Quartz, which can crystallise together at -the same time in the plutonic rocks, forming a granular intergrowth in which none of the minerals are euhedral, and most are anhedral (the texture is called a hypidiomorphic granular texture). Some hornblende or mica may be present and as these minerals started to crystallise rather earlier they are often subhedral.

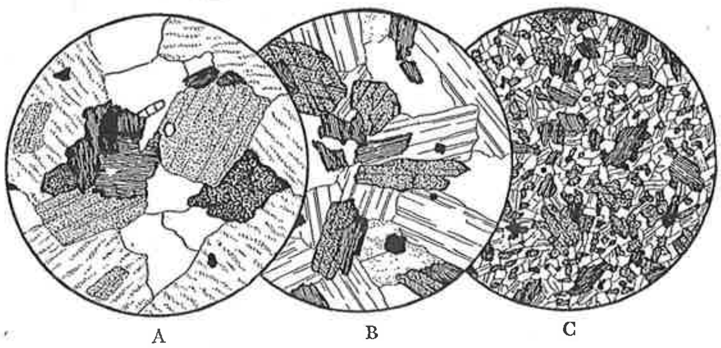
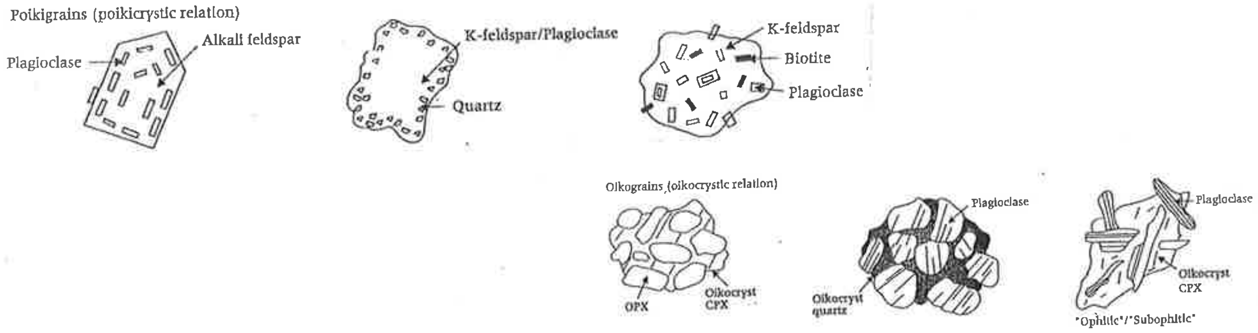


Figure . Granite and Granodiorites

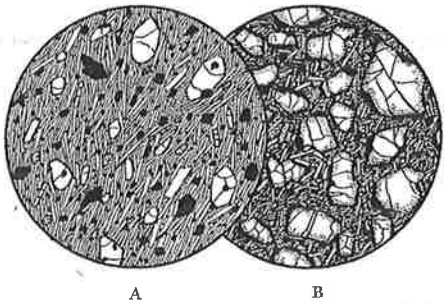
Intergrowth and enclosure

As the minerals crystallising together begin to 'compete' with one another, an intergrowth can occur. If one mineral is growing more quickly it can surround and enclose the other. Partial enclosure results in an **Ophitic texture** - complete enclosure results in a **Poilcilitic texture.** These textures are seen in slowly cooled plutonic rocks such as gabbros. In more rapidly cooled rocks such as in dykes, sills and other shallow intrusions, ophitic texture is the most common - it used to be called the "doleritic" texture, as many basaltic dykes are doleritic.



Volcanic

Lavas which erupt to the surface don't show ophitic textures; they cool much more quickly and usually contain a scattering of larger crystals which formed at depth, known as phenocrysts - set in a fine-grained groundmass or matrix made up of all the remaining minerals (**porphyritic texture**). These groundmass crystals have crystallised rapidly from a super-cooled liquid and often form a mesh of plagioclase crystals (long and narrow), in the interstices of which are found rounded granules of pyroxene and iron oxides. This is an **interstitial** texture.

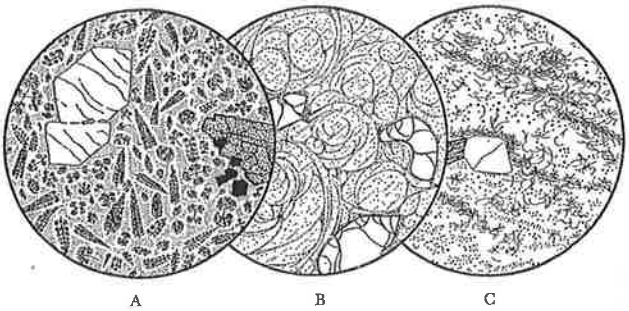


Figure

Basalts

Erupted rhyolites - may carry phenocrysts of quartz or feldspar, but the liquid is much cooler than the basalt liquid and commonly freezes before fully crystallising. The groundmass may thus contain some very small crystallites, but is often mainly glass (glass is isotropic). The glass is unstable over geological time and will eventually devitrify to give a dense fine-grained mat of the residual minerals - quartz and feldspar in the rhyolites. In the devitrification process, firstly shrinkage produces curved cracks - Perlitic cracks - and then crystal growth starts from scattered nuclei at which radiating clusters of tiny crystallites of feldspar form spherulites.

IGNEOUS ROCKS



Rhyolitic Pitchstones with Microlites and Crystallites

Igneous Petrography Glossary

Crystallinity

Holocrystalline —— 100% crystal	hypocrystalline ——	**holohyaline** 100% glass

Granularity

Coarse	>5mm	**Plutonic**
Medium	1-5mm	**Hybabyssal**
Fine	<1mm	**Volcanic**

equigranular – approximately the same size
inequigranular – crystals differ substantially in size e.g. porphyritic

microcrystalline – identifiable in thin section
cryptocrystalline – unidentifiable in thin section

Crystal morphology

euhedral – crystals completely bound by its characteristic faces.
subhedral – crystals bound by only some of its faces.
anhedral – lack of any characteristic faces.
skeletal – hollows and gaps
embayments – round dissolution holes on crystal surface
dendritic – regular array of fibres sharing a common optical orientation (i.e. 1 crystal)
sieve textured crystal – small, interconnected, box shaped crystal – spongy appearance

Textures

porphyritic texture – relatively large crystals (phenocrysts) are surrounded by finer grained crystals of the groundmass.
glomeroporphyritic texture porhyritic texture with phenocrysts are bunched/ clustered in aggregates/ clots called glomerocrysts.
glomerocryst – means 1 type of mineral in a clot
poikilitic texture – relatively large crystals of one mineral encloses numerous smaller crystals (randomly orientated)

oikocryst – (enclosing crystal) – host crystal
chadacryst - enclosed crystal

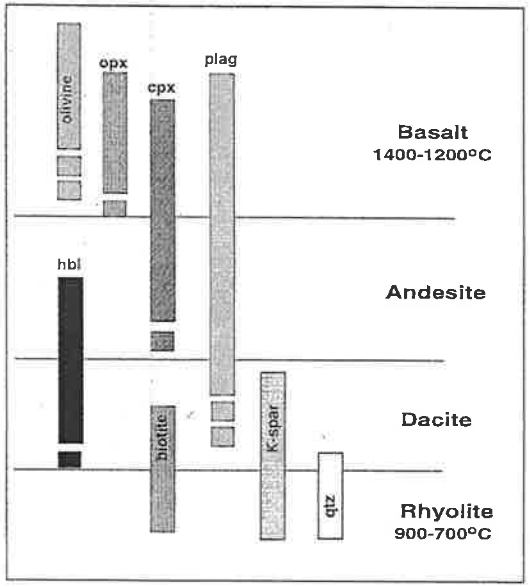
ophitic texture – randomly arranged chadacrysts are elongated and are wholly or partly enclosed by oikocryst e.g. plagioclase surrounded by subequant augite.

interstitial – basis of material occupying angular spaces between feldspar laths.
intersertial – glass or hypocrystalline material partially or wholly occupies wedged shaped indices. Glass can be altered.
intergranular – spaces between laths are occupied by 1 or more grains of Px (± Ol and opaques)
trachytic texture – sub-parallel arrangement of microcrystalline lath shaped feldspars in groundmass of holo or hyalocrystalline rock.
trachytoid texture – sub-parallel arrangement of tabular, bladed or prismatic crystals visible to naked eye.
perthitic/antiperthitic – plagioclase in feldspar or vice versa
corona texture – crystals of one mineral surrounded by rim/mantle of 1 or more crystals of another mineral e.g. ol surrounded by opx or hbl by biot.

Zoning

zoning – solid solution composition from rim to core
normal – high to low e.g. An → Ab rich plagioclase
reversed – low to high e.g. Ab → An plagioclase
continuous – gradual changes
discontinuous – abrupt changes

Mineralogy



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— SUMMARY TABLE —

Thin section Slide No.	OLIVINE	OPX	CPX	AMPHIBOLE	BIOTITE	MUSCOVITE	PLAGIOCLASE	ALK. FELDS.	QUARTZ	ORE	ROCK NAME + COMMENTS

Homework 1
Geochemistry / Igneous Petrology

Petrogenetic modelling using mass balance calculations

$$C_j = \sum_{i=1}^{n} \alpha_i M_{i,j} \quad \text{.......................... equation 1}$$

in major oxide terms this equation translates as:

C_j = concentration (%) of element j in the rock,
$M_{i,j}$ = concentration (%) of element j in component i (a component could be a mineral, a rock composition, an end-member magma),
α_i = fraction of component i
n = number of components

PROCESS	------- COMPOSITION ------- C_j	$M_{i,j}$	FRACTION α_i
Magma mixing	Hybrid rock	End-member 1 End-member 2	α $(1 - \alpha)$
Fractional crystallisation	Parental magma	Extracted crystals Residual magma	$\Sigma\alpha_i$ $(1 - \Sigma\alpha_i)$

Exercise (1) Magma mixing

You are given the composition of a dacite magma, and your hypothesis is that it is the result of mixing between an andesite and a rhyolite magma. Try to find the proportions (αs in the equation above) of the two end-member magmas involved in magma mixing. Examine the table (overleaf), and estimate (?guesstimate) the likely proportions of each end-member magmas that you would require to mix together to approximate the composition of the mixed magma (dacite).
Rearrange equation (1) to express your magma mixing model and calculate the results for each oxide. Estimate the "goodness of fit" using r^2 as indicated (a value of < 1.0 is usually taken as acceptable).

Note that $DACITE_{obs}$ is the analysed composition of the dacite while $DACITE_{calc}$ is the estimated composition derived by blending appropriate proportions of rhyolite and andesite. Find the values of α for andesite and rhyolite that gives *your* best match for $DACITE_{obs}$.

	end-member 1 RHYOLITE	*end-member 2* ANDESITE	*mixed magma* $DACITE_{obs}$	*calculated mix* $DACITE_{calc}$	r^2 $(OBS - CALC)^2$
SiO_2	73.95	58.70	65.98		
TiO_2	0.28	0.88	0.59		
Al_2O_3	13.48	17.24	16.15		
Fe_2O_3	1.50	3.31	2.47		
FeO	1.13	4.09	2.33		
MgO	0.40	3.37	1.81		
CaO	1.16	6.88	4.38		
Na_2O	3.61	3.53	3.85		
K_2O	4.37	1.64	2.20		
P_2O_5	0.07	0.21	0.15		

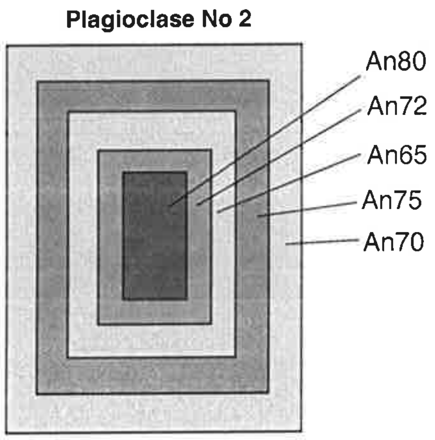
Goodness of fit = Σr^2 =

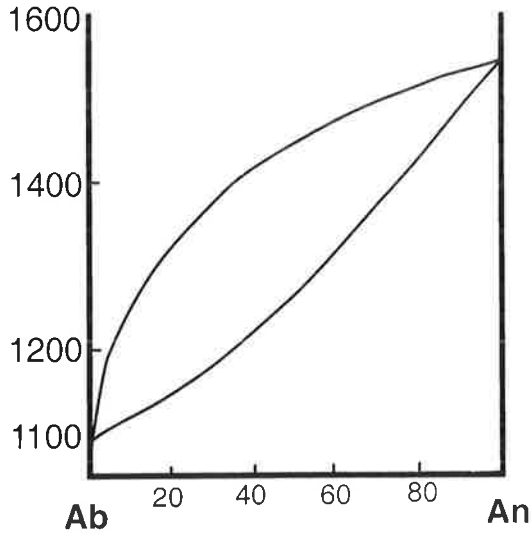
Exercise (2) Fractional crystallisation

If 30% of a diorite magma crystallises as amphibole and 25% as plagioclase then find the composition of the residual melt for each oxide.

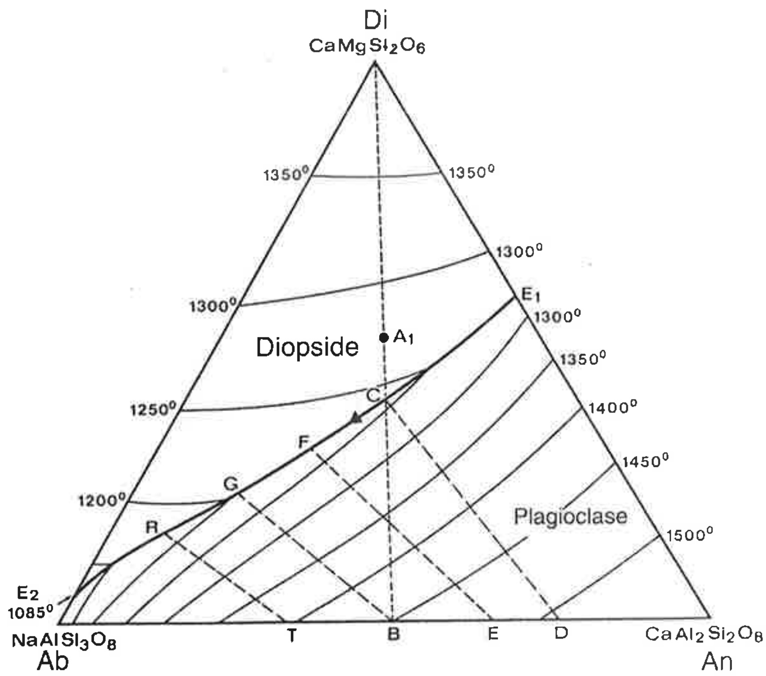
	Diorite	Amphibole	Plagioclase	new magma
SiO_2	57.48	44.99	58.10	
TiO_2	0.95	1.46	0.00	
Al_2O_3	16.67	11.21	26.44	
Fe_2O_3	2.50	3.33	0.04	
FeO	4.92	13.17	0.15	
MgO	3.71	10.41	0.03	
CaO	6.58	12.11	7.84	
Na_2O	3.54	0.97	6.48	
K_2O	1.76	0.76	1.10	
P_2O_5	0.29	0.00	0.00	

Homework 2
Geochemistry/Igneous Petrology





1. Describe the crystallisation history of plagioclase crystal No 2, using the An-Ab solid solution phase diagram . What has happened in the magma chamber ? Write a brief outline of your explanation. Note there is more than one possible scenario!



2. Consider equilibrium crystallisation for a starting composition of 30% $An_{40}Ab_{60}$ and 70% Di in the system Di-An-Ab. Estimate the composition of the final liquid ?

Homework 3
Geochemistry / Igneous Petrology

1. Partition coefficients and bulk distribution coefficients

The distribution of a trace element between silicate liquid and crystal is described by the *partition* (or *distribution*) *coefficient:*

$$K_{D_j} = \frac{C_{j,\,mineral}}{C_{j,\,melt}}$$

For an assemblage of minerals crystallising from a magma the *bulk distribution coefficient.* (D) is

$$D_j = \sum_{i=1}^{n} w_i K_{D_{i,j}}$$

where w_i is the mass fraction of mineral i,
and $K_{D_{i,j}}$ is the partition coefficient for element j in mineral i.

Taking the example of Ce in a peridotite comprising of 60% olivine, 30% opx, 5% cpx and 5% garnet: The K_D values for these minerals in basic melt are given in the table below:

	w	$K_{D_{Ce}}$	$K_{D_{Ni}}$
Olivine	0.60	0.007	10
Opx	0.30	0.02	5
Cpx	0.05	0.15	8
Garnet	0.05	0.03	0.01
	1.00		

$$D_{Ce} = \underset{olivine}{0.60 \times 0.007} + \underset{opx}{0.30 \times 0.02} + \underset{cpx}{0.05 \times 0.15} + \underset{garnet}{0.05 \times 0.03}$$

$$= 0.019$$

<u>Exercise</u>

Calculate the bulk distribution coefficient for Ni (D_{Ni}) in the same peridotite.

2. Spidergrams

The so-called *spidergrams* are line plots of the ratio:

$$\frac{\text{rock concentration}}{\text{reference composition}}$$

of a range of elements plotted in a particular sequence along the X-axis (see Rollinson section 4.4 or Wilson p19 for explanation). The ratio is plotted on the Y-axis with a logarithmic scale (0.1, 1, 10, 100, 1000 etc., as appropriate).

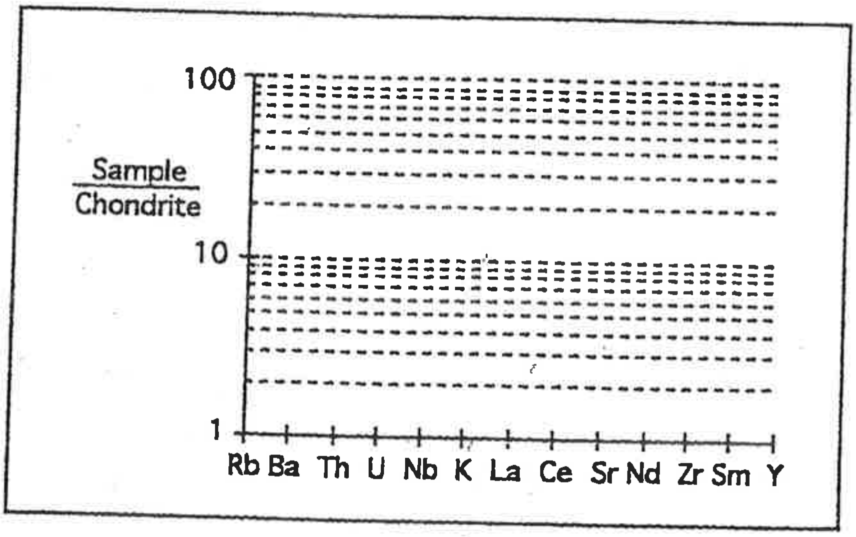
The *normalisation* or *reference* standard may be a chondrite (to represent bulk earth composition) or MORB, or other source rock compositions. Rollinson (p143) has a list of appropriate reference values as well as lists of various X-axis element combinations.

Exercise

Compare two types of basalt from contrasting settings by plotting their chondrite-normalised spidergrams on the same graph. The basalts are a mid ocean ridge basalt of "normal" composition (N-type MORB) and a tholeiitic basalt from an island arc (IAT).

Plot your ratios on the template provided below. (Abundances for trace elements are normally quoted in parts per million, or ppm).

Element	N-type MORB	Island arc basalt	Chondrite
Rb	1.0	14	0.35
Ba	12	300	6.9
Th	0.20	1.1	0.042
U	0.10	0.36	0.013
Nb	3.1	1.4	0.35
K	1060	8640	120
La	3.0	10	0.328
Ce	9.0	23	0.865
Sr	124	550	11.8
Nd	7.7	13	0.63
Zr	85	40	6.84
Sm	2.8	2.9	0.20
Y	29	15	2.0



Briefly describe the differences between the two samples and outline one or more possible reasons for these differences.

Homework 4

Geochemistry / Igneous Petrology

The behaviour of trace elements during partial melting can be modelled in two end-member cases. (In nature the equilibrium case is probably closer to reality.)

Batch melting model

Melting is regarded as taking place as a batch in equilibrium with residue before removal of any melt.

$$\frac{C_L}{C_0} = \frac{1}{D(1-F)+F}$$

where C_0 = initial composition of *source rock*,
C_L = concentration of element in liquid (melt),
D = bulk distribution coefficient for that element,
and F = fraction of melt (i.e. 1= all melt, 0 = all solid as crystal residue, no melt).

Perfect fractional (Rayleigh) melting model

In this case each infinitesimally small increment of melt is removed from contact with the source rock. This is physically unrealistic but represents an end-member case.

$$\frac{C_L}{C_0} = \frac{1}{D}(1-F)^{(\frac{1}{D}-1)}$$

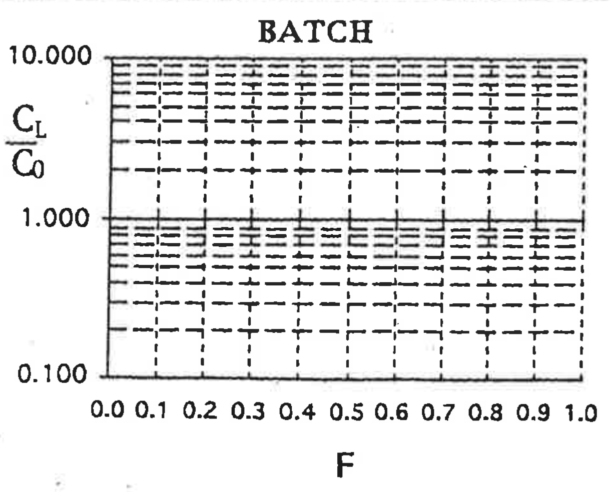
Exercise

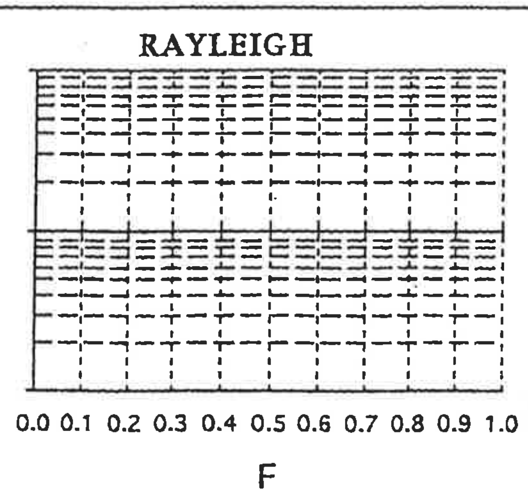
Calculate the C_L/C_0 ratios for both the batch and Rayleigh melting of an incompatible element with D = 0.1 and a compatible element with D=10.

Perform the calculations for 10%, 30%, 50%, 70%, and 90% melting and complete the table below.

F	*BATCH*		*RAYLEIGH*	
	$\frac{C_L}{C_0}$ (D=0.1)	$\frac{C_L}{C_0}$ (D=10)	$\frac{C_L}{C_0}$ (D=0.1)	$\frac{C_L}{C_0}$ (D=10)
0.1				
0.3				
0.5				
0.7				
0.9				

Graph the results on the templates (one each for equilibrium and Rayleigh):





RADIOGENIC ISOTOPES

A radiogenic isotope system is one where a daughter isotope produced through radioactive decay of a parent isotope. Normally the daughter isotope is considered in relation to a stable isotope of the same element.

The basic radioactive decay equation may be expressed as:

$$D = D_0 + N(e^{\lambda t} - 1) \quad \text{................. (equation 1)}$$

where D = total no.of daughter atoms,
D_0 = no.of radiogenic daughter atoms present initially,
N = no.of parent atoms remaining,
t = time,
λ = decay constant ($\lambda = \frac{\ln(2)}{T_{\frac{1}{2}}} = \frac{0.693}{T_{\frac{1}{2}}}$ where $T_{\frac{1}{2}}$ = half life)

Equation 1 may be arranged as:

$$^{87}Sr = {}^{87}Sr_i + {}^{87}Rb(e^{\lambda t} - 1) \quad \text{.............. (equation 2)}$$

where ^{87}Sr and ^{87}Rb are the present day values and $^{87}Sr_i$ is the initial value before the system closed and decay began.
As ^{86}Sr is a stable isotope this will not change with time, and we may divide through each term in equation 2 by this factor:

$$\frac{^{87}Sr}{^{86}Sr} = \left(\frac{^{87}Sr}{^{86}Sr}\right)_i + \frac{^{87}Rb}{^{86}Sr}\left(e^{\lambda t} - 1\right) \quad \text{...........(equation 3)}$$

This equation is the basis for Rb-Sr geochronology.

When the age (t) is accurately known, then the initial ratio for the Sr isotopes (variously written as $\left(\frac{^{87}Sr}{^{86}Sr}\right)_i$, $\left(\frac{^{87}Sr}{^{86}Sr}\right)_0$, or $\left(\frac{^{87}Sr}{^{86}Sr}\right)_t$ where t is the age in Ma) can be more accurately calculated for each sample using the following rearrangement of equation 3:

$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_i = \frac{^{87}Sr}{^{86}Sr} - \frac{^{87}Rb}{^{86}Sr}\left(e^{\lambda t} - 1\right) \quad \text{...........(equation 4)}$$

Text support: Rollinson Chapter 6, Chapter 7 (section 7.2).

Exercise 1:

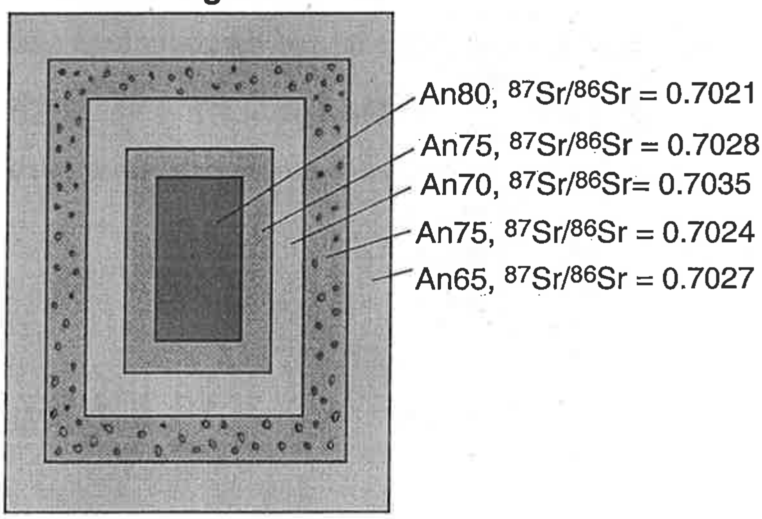
Assuming an age (t) of 430Ma and using the decay constant for the Rb-Sr system (λ = 1.42×10^{-11} y^{-1}, find the initial ratios for the following 4 granite samples (equation 4):

Sample	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$\left(\frac{^{87}Sr}{^{86}Sr}\right)_t$
A	0.1973	0.70607	
B	1.738	0.72080	
C	1.686	0.72049	
D	0.9055	0.71373	

Exercise 2:

The plagioclase crystal below was analysed for major elements (An mol%) and for Sr isotope composition of its individual zones. Plot its An mol% and its Sr isotope composition vs. the position in the crystal (e.g. core, zone 1, zone 2 ... on x-axis). Briefly discuss possible causes for the variations observed.

Zoned Plagioclase



Homework No 6
Geochemistry/Igneous Petrology

Contrasting radiogenic isotopes, that do not change by physical influence (Δ P, T) or fractional crystallisation, oxygen isotopes fractionate during partial melting and during crystal-liquid fractionation. This is because the mass difference between oxygen isotopes is much bigger due to their smaller weight, relative to the mass difference of e.g. Nd isotopes. However, at magmatic temperatures this fractionation is small (ca. 0.2‰ per 5wt% SiO_2).

Therefore primitive basaltic magmas should have an isotope composition reflecting their mantle source (5.5-6‰). Evolved rocks such as granites and rhyolites should hence be enriched in $\delta^{18}O$ by ca. 1‰ assuming closed system differentiation and a SiO_2 increase of ca. 25 wt%.

To assess differences between end member compositions within a suite of samples the difference (Δ) of their oxygen isotope values is commonly used. For example the difference between a rhyolite and a basalt can be expressed as $\Delta_{rhyolite-basalt} = \delta^{18}O_{rhyolite} - \delta^{18}O_{basalt}$. This method is also used to evaluate differences between mineral pairs that help constrain oxygen fractionation throughout a sample suite.

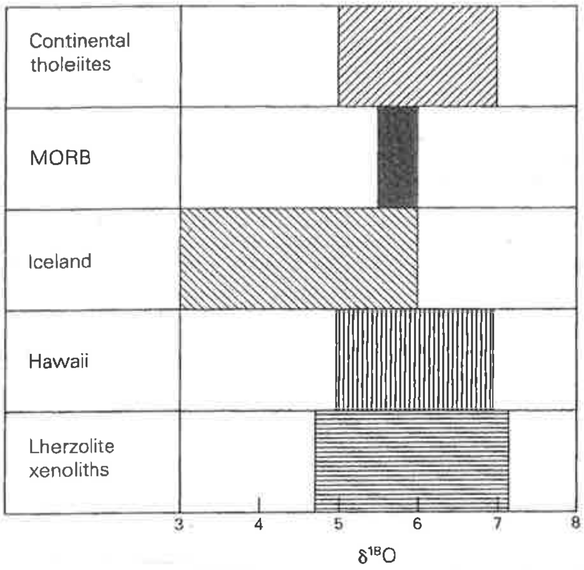
Exercise 1.

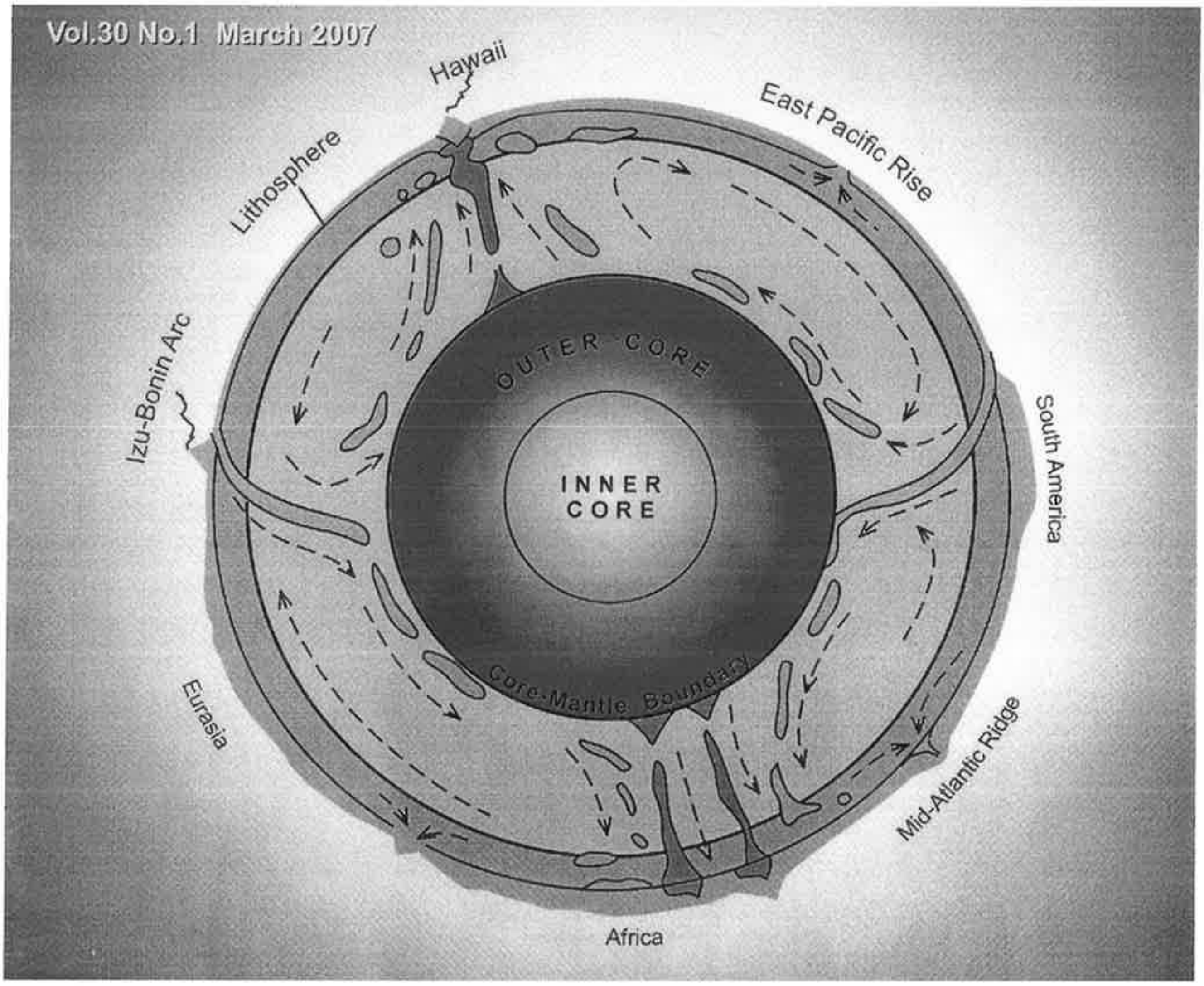
The following five samples from a recently erupted volcano yield $\delta^{18}O$ values that are markedly different. Calculate the $\Delta_{rhyolite-basalt}$ and briefly discuss the likelihood of the suite having evolved in an open vs. a closed system.

Sample	SiO_2	$\delta^{18}O_{wr}$	$\delta^{18}O_{px}$	$\delta^{18}O_{fsp}$	Δ_{fsp-px}
Basalt	46	5.6	5.3	5.5	
Basaltic Andesite	53	6.1	5.8	6.0	
Andesite	59	6.6	6.2	6.5	
Dacite	65	6.9	6.6	6.9	
Rhyolite	72	7.4	7.0	7.3	

Exercise 2.

Calculate the Δ_{fsp-px} values of the five samples and comment on the results (i.e. are they consistent with the results you derived from the whole rock data?).


Continental tholeiites
MORB
Iceland
Hawaii
Lherzolite xenoliths
3
4
5
6
7
8
δ18O


Vol.30 No.1 March 2007
Hawaii
East Pacific Rise
Lithosphere
Izu-Bonin Arc
OUTER CORE
INNER CORE
South America
Core-Mantle Boundary
Eurasia
Mid-Atlantic Ridge
Africa

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